

## **WHAT IS CLAIMED IS:**

1. A method of simulating an image of a patterned mask having a mask function in the spatial frequency domain, the image to be formed by a projection system having a defocus amount  $z$  along an optical axis, the projection system including pupil optics, the method comprising:
  - providing a source function having a center spatial frequency coordinate;
  - providing a first paraxial pupil function of the pupil optics at a first offset relative to said center spatial frequency coordinate and providing a second paraxial pupil function of the pupil optics at a second offset relative to said center spatial frequency coordinate;
  - forming an integrand comprising a product of functions including said source function, said first paraxial pupil function, and said second paraxial pupil function;
  - defining an integration region spanning the intersection of said source function with said first and second paraxial pupil functions, said integration region having a boundary comprising a finite number of arcs;
  - integrating said integrand for each of said finite number of arcs to obtain a finite number of contour integrals each corresponding to one of said finite number of arcs, wherein each of said finite number of contour integrals comprises an analytical solution; and
  - determining a transmission cross-coefficient (TCC) comprising a sum of said finite number of contour integrals.
2. The method of claim 1 wherein said first and second paraxial pupil functions each has a phase term that is approximated by a second order Taylor expansion.
3. The method of claim 1 wherein each of said arcs are circular arcs having a subtended angle  $\phi$  relative to the center of the corresponding circle of said arc.

4. The method of claim 3 wherein said integrand is parameterized in terms of a square root of one plus the cosine of said subtended angle  $\phi$ , and wherein said square root is approximated by an expansion having an error term, wherein said expansion has a finite number of terms L, wherein L is sufficiently large that said error term is smaller than a predetermined error tolerance.

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5. The method of claim 4, wherein said expansion has L parameters  $f_m$ , where m ranges from 1 to L, said parameters determined by a curve fit to the square root of one plus the cosine of said subtended angle  $\phi$ .

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6. The method of claim 5 wherein said parameters  $f_m$  comprise a polynomial expansion of the form  $\left(1 + \sum_{m=1}^L f_m (\cos \phi)^m\right)$ .

7. The method of claim 6 wherein said finite number of terms L is 4.

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8. The method of claim 1 wherein the projection system has a numerical aperture (NA) between about 0.5 to 0.7.

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9. The method of claim 1 further comprising the step of determining image intensity in accordance with a Hopkins model using said TCC integral.

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10. The method of claim 9 wherein the projection system has a numerical aperture (NA) greater than about 0.7, and wherein said image intensity is determined at a coordinate  $\vec{x}$  orthogonal to the optical axis, and said method further comprises dividing said coordinate  $\vec{x}$  by the square root of a nonparaxial correction factor  $(1 + NA^2 g(\vec{x}, z)^2)$  and dividing

said image intensity by the square of said nonparaxial correction factor, wherein

$$g(\bar{x}, z) = \frac{|\bar{x}|}{(NAz) \left( 1 + \frac{9\lambda^4}{256\pi^8 NA^8 z^4} \right)} \text{ for an illumination comprising a wavelength of } \lambda.$$

11. The method of claim 1 further comprising determining an aberration pupil function comprising an exponential of a phase term, said phase term expressed by a closed form polynomial series with respect to a deviation  $\varepsilon_w$  from a spherical lens, wherein said exponential is Taylor expanded in terms of said deviation  $\varepsilon_w$  to a specified order, wherein said step of forming an integrand further comprises multiplying each of said first and second paraxial pupil functions by said aberration pupil function.

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12. The method of claim 11 wherein said closed form polynomial series comprises Zernike polynomials.

13. The method of claim 1 further comprising determining an apodization pupil function comprising a factor representing amplitude variations across the pupil, and wherein said step of forming an integrand further comprises multiplying each of said first and second paraxial pupil function by said apodization pupil function.

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14. The method of claim 13 wherein the projection system has a numerical aperture (NA) greater than about 0.7.

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15. A computer program product comprising computer readable storage medium having stored therein computer readable instructions executable by the computer for causing a computer to perform method steps for simulating an image of a patterned mask having a mask function in the spatial frequency domain, the image to be formed by a projection system having a defocus amount  $z$  along an optical axis, the projection system including pupil optics, the method steps comprising:

- providing a source function having a center spatial frequency coordinate;
- providing a first paraxial pupil function of the pupil optics at a first offset relative to said center spatial frequency coordinate and providing a second paraxial pupil function of the pupil optics at a second offset relative to said center spatial frequency coordinate;
- 5 providing an integrand comprising a product of functions including said source function, said first paraxial pupil function, and said second paraxial pupil function;
- defining an integration region spanning the intersection of said source function with said first and second paraxial pupil functions, said integration region having a boundary comprising a finite number of arcs;
- 10 integrating said integrand for each of said finite number of arcs to obtain a finite number of contour integrals each corresponding to one of said finite number of arcs, wherein each of said finite number of contour integrals comprises an analytical solution; and
- 15 determining a transmission cross-coefficient (TCC) comprising a sum of said finite number of contour integrals.
16. The computer program product of claim 15 wherein said first and second paraxial pupil functions each has a phase term that is approximated by a second order Taylor expansion.
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17. The computer program product of claim 15 wherein each of said arcs are circular arcs having a subtended angle  $\phi$  relative to the center of the corresponding circle of said arc.
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18. The computer program product of claim 17 wherein said integrand is parameterized in terms of a square root of one plus the cosine of said subtended angle  $\phi$ , and wherein said square root is approximated by an expansion having an error term, wherein said expansion has a finite number of terms L, wherein L is sufficiently large that said error term is smaller than a predetermined error tolerance.

19. The computer program product of claim 18, wherein said expansion has L parameters  $f_m$ , where m ranges from 1 to L, said parameters determined by a curve fit to the square root of one plus the cosine of said subtended angle  $\phi$ .

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20. The computer program product of claim 19 wherein said parameters  $f_m$  comprise a polynomial expansion of the form  $\left(1 + \sum_{m=1}^L f_m (\cos \phi)^m\right)$ .

10 21. The computer program product of claim 20 wherein said finite number of terms L is

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22. The computer program product of claim 15 wherein the projection system has a numerical aperture (NA) between about 0.5 to 0.7.

15 23. The computer program product of claim 15 wherein said method steps further comprise the step of determining image intensity in accordance with a Hopkins model using said TCC integral.

20 24. The computer program product of claim 23 wherein the projection system has a numerical aperture (NA) greater than about 0.7, and wherein said image intensity is determined at a coordinate  $\bar{x}$  orthogonal to the optical axis, and said method steps further comprise dividing said coordinate  $\bar{x}$  by the square root of a nonparaxial correction factor  $(1 + NA^2 g(\bar{x}, z)^2)$  and dividing said image intensity by the square of said nonparaxial

correction factor, wherein  $g(\bar{x}, z) = \frac{|\bar{x}|}{(NAz) \left( 1 + \frac{9\lambda^4}{256\pi^8 NA^8 z^4} \right)}$  for an illumination

25 comprising a wavelength of  $\lambda$ .

25. The computer program product of claim 15 wherein said method steps further comprise providing an aberration pupil function comprising an exponential of a phase term, said phase term expressed by a closed form polynomial series with respect to a deviation  $\varepsilon_w$  from a spherical lens, wherein said exponential is Taylor expanded in terms

5 of said deviation  $\varepsilon_w$  to a specified order, wherein said step of providing an integrand further comprises multiplying each of said first and second paraxial pupil functions by said aberration pupil function.

10 26. The computer program product of claim 25 wherein said closed form polynomial series comprises Zernike polynomials.

15 27. The computer program product of claim 15 wherein said method steps further comprise providing an apodization pupil function comprising a factor representing amplitude variations across the pupil, and wherein said step of providing an integrand further comprises multiplying each of said first and second paraxial pupil function by said apodization pupil function.

28. The computer program product of claim 27 wherein said wherein the projection system has a numerical aperture (NA) greater than about 0.7.

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